High Power Testing of ANL X-Band Dielectric-Loaded Accelerating Structures

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Abstract. A program is underway at Argonne National Laboratory to develop RF-driven dielectric-loaded accelerating (DLA) structures with the ultimate goal of demonstrating a compact, high-gradient linear accelerator based on this technology. In the first part of this program, as previously reported on, DLA structures were successfully designed, numerically modeled, constructed, vacuum tested, and cold tested with a network analyzer. In this paper, we report on the next stage of the program, the recent results of high power tests carried out on two DLA prototypes at the 11.424-GHz magnicon facility at the Naval Research Laboratory. The purpose of these tests was to study the DLA structure under high power conditions in order to look for signs of dielectric breakdown, a fundamental issue for this technology. In two separate series of experiments, the magnicon powered both a traveling-wave and standing-wave DLA structure. A discussion of results and future directions for this program will be presented.

INTRODUCTION

As conventional copper-based accelerating structures continue to be pushed toward their ultimate operating limits by the NLC and CLIC, interest in developing alternative slow-wave structures that may surpass these limits is growing [1-4]. One such structure, which is the focus of this paper, is the dielectric-loaded accelerator (DLA, see Fig. 1) that consists of a dielectric-lined cylindrical waveguide of inner radius a, outer radius b, length L, and dielectric constant ε, driven by an external RF source. This structure can be operated as a slow-wave accelerator by adjusting these parameters until the phase velocity is c.

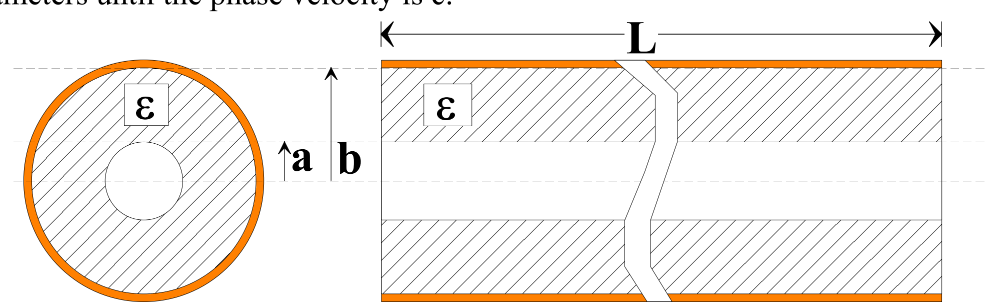


FIGURE 1. The Dielectric-Loaded Accelerating Structure.

Although there are several potential advantages of DLA structures over metallic disk-loaded structures [5], several concerns have been raised about the feasibility of making these devices into practical accelerators. And while much progress has been made on many of these issues, some major questions remain [6, 7]. For example, a fundamental concern for this technology that has yet to be resolved is RF breakdown of the dielectric in the presence of high electric fields – i.e. dielectric breakdown. At present, there is little information available on this topic in the literature.

An experimental program was recently started by Argonne National Laboratory (ANL) to develop an RF-driven X-band DLA structure. The ultimate goal of the program is to make a complete, dielectric-based compact accelerator consisting of an electron source followed by a dielectric-based accelerating linac. To accomplish this, we will use a 24-cell, 11.424-GHz RF thermionic electron gun [8] for the electron injector, a DLA structure, and the 11.424-GHz magnicon [9] at the Naval Research Laboratory (NRL) to power both the gun and the structure. The exact energy produced by the compact accelerator will depend on which structure is used, but for reference we give the expected range. Using 50 MW of RF power to power the gun and the structure of Ref. [6], we expect that the electron gun will produce a beam of 3 to 5 MeV, and that the DLA structure will add another 10 to 20 MeV, for a final energy of 12 to 25 MeV

In the first stage of the program [6], several problems were solved including (1) demonstration of efficient RF coupling into a DLA structure; (2) showing that gas absorption in the dielectric didn't prevent the structure from reaching good operating vacuum; and (3) showing that the dielectric properties were not overly sensitive to temperature. In this paper, we report on the next stage of this program, in which high power tests were recently carried out at NRL to address the dielectric breakdown issue. During the high power tests, two DLA structures were studied, a traveling-wave (TW) and a standing-wave (SW) dielectric-lined waveguide.

DIELECTRIC-LOADED ACCELERATING STRUCTURES

In this section, we describe the dimensions and physical properties of the TW-DLA structure and the SW-DLA structure that underwent high power testing at NRL. The operating principle of the structures can be found in Refs. [1, 6].

Traveling-Wave Accelerating Structure

The TW-DLA structure (Fig. 2) is an X-band (11.424-GHz) constant impedance accelerator operating in the TM_{01} mode with a group velocity of 0.06c. The dielectric material used is a commercially available MgCaTi-based ceramic [10] with a dielectric constant of 20 and a manufacturer specified loss tangent of 10^{-4}. RF power is fed into and extracted from the tube using WR-90 waveguide with SLAC-type flanges. The RF power is magnetically coupled in through a side-wall coupling slot with a tapered dielectric directly underneath the slot to improve the impedance match into the structure. Details of the structure are given in Table 1.

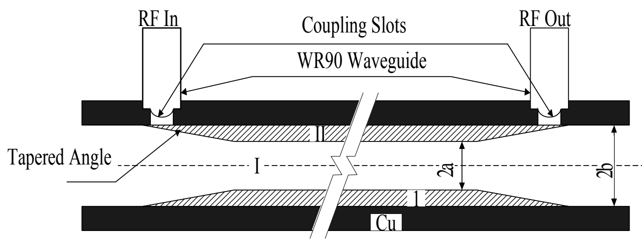


FIGURE 2. The Dielectric Loaded Accelerating Structure Prototype.

Standing-Wave Accelerating Structure

The physical layout of the SW-DLA structure is similar to that of the TW shown in Fig. 2, with the obvious exception that it does not have an output waveguide. The dielectric material is a commercially available MgCaTi-based ceramic [11] with a dielectric constant of 17 and a loss tangent of 10^{-4}. Details are given in Table 1.

TABLE 1. Dimensions and Physical Properties of the Two DLA Prototypes.

	Traveling-Wave DLA Structure	Standing-Wave DLA Structure
Dielectric Material	MgCaTi ceramic	MgCaTi ceramic
Frequency	11.424-GHz	11.424-GHz
Phase Velocity	c	c
Operating Mode	$TM_{0,1}$	$TM_{0,1,n}$
Relative Dielectric Constant	20	17
Dielectric Inner Radius	3 mm	3 mm
Dielectric Outer Radius	4.5 mm	4.7 mm
Length of Structure	25 cm	25 cm
Dielectric Taper	8 degrees	8 degrees
Coupling Slot Size	4.7 mm x 5.7 mm	~2 mm x ~3 mm
Coupling Efficiency	S_{11} = -20 dB S_{21} = -1.7 dB	S_{11} = -10 dB

EXPERIMENTAL SETUP FOR THE HIGH POWER TESTS

In this section we describe (Fig. 3) the physical layout and the diagnostics used during the high power tests carried out on both prototypes – i.e. the TW-DLA structure and the SW-DLA structure described in the previous section.

The magnicon output is equally split between two WR-90 vacuum waveguides, each equipped with a vacuum window (not shown), a -55.5 dB bi-directional coupler connected to calibrated crystal detectors, and a SLAC-type high-power load. Our device under test (D.U.T.) was installed at the end of one of the output arms in place of the load. The diagnostics available to monitor the D.U.T. during high power conditioning included (1) bi-directional couplers on both the input and output waveguide; (2) four ion pumps (Fig. 3: IP1-4) to monitor pressure during an arc; (3) a Faraday cup downstream of the structure to monitor dark current; (4) a thermocouple

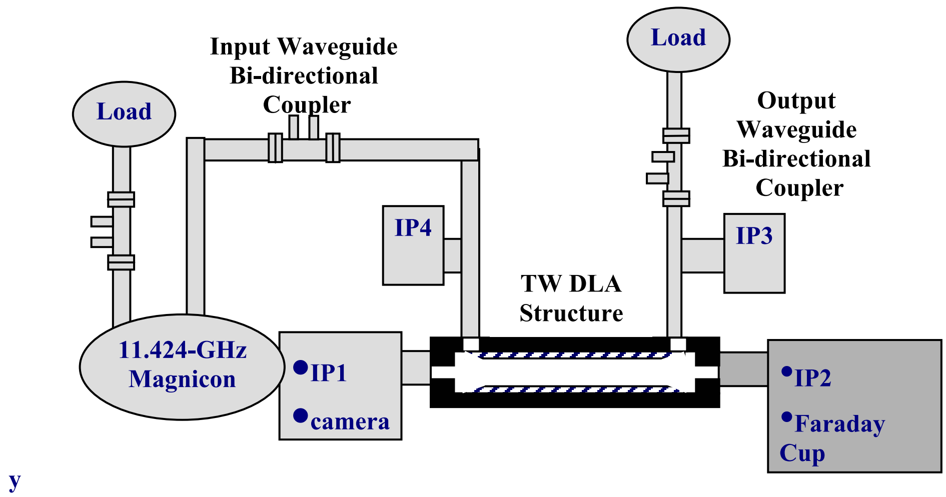


FIGURE 3. Block diagram of the experimental setup used to conduct the high power test of the traveling-wave DLA structure at NRL. The hashed region was not present during the test of the standing-wave DLA structure, since that structure has only a single coupling port.

on the D.U.T. to monitor temperature; and (5) a camera to look for visible light along the axis of the structure during an arc. In each case, the D.U.T. underwent a 150^{o}C in situ bake for 3-5 days before high power conditioning tests were initiated.

The testing of each D.U.T. was conducted by slowly increasing the output power of the magnicon, beginning from a low power level, while monitoring all the diagnostics to look for signs of breakdown. Typically, after an increase in the power level, the voltage signals from the bi-directional couplers were acquired with an oscilloscope and the vacuum pressure and D.U.T. temperature were recorded in the log. For the TW-DLA structure, we monitored the forward, reflected, and transmitted power by recording the forward and reflected power of the bi-directional coupler on the input waveguide and the forward power of the bi-directional coupler on the output waveguide, respectively. For the SW-DLA structure, we monitored the forward and reflected power by measuring the forward and reflected power from the bi-directional coupler on the input waveguide. If either a visible light flash on the monitor or a non-zero reading on the Faraday cup ammeter were observed, the event was to be noted in the log.

EXPERIMENTAL RESULTS AND DISCUSSION

In this section we present the results of the high power tests carried out on both prototypes and discuss the meaning of the results obtained.

No visible arcs and no dark current were observed at any point during either high power test. This is a strong indication that there was no breakdown in the either of the accelerating structures. The typical vacuum pressure (P) during the test of the TW-DLA was $P < 10^{-7}$ Torr and it was $P < 10^{-8}$ Torr for the SW-DLA structure. During the tests, an arc was indicated by (1) a sharp rise in pressure indicated by the ion pump current; and (2) an abrupt change of the forward, reflected and transmitted signals monitored on the oscilloscope.

Traveling-Wave Accelerating Structure Test

During the high power test of the traveling-wave structure, the magnicon output pulse width was varied from 200 nsec at the beginning to 600 nsec at the end. The high power test was performed over a period of 3 days for an integrated run time of about 20 hours. The TW-DLA structure conditioned similarly to a metallic cavity in that the vacuum pressure would rise after an increase in power and then gradually drop back down to the pre-arc level.

At low input power (~10 kW), very little arcing was observed and S_{21} (transmission) was measured to be about -5 dB. The structure eventually conditioned to a power level consistent with a 3 – 5 MV/m acceleration gradient (Fig. 4a) in the cavity with no signs of damage. The data corresponding to this gradient is shown in Fig. 4 with an input power of 600 kW, a reflected power of 40 kW, and a transmitted power of 170 kW. From this, we calculated the power transmitted corresponded to S_{21} = -5.5 dB. This number is lower than expected since benchtop measurements done before the high power test measured S_{21} to be -3dB. The fact that transmitted power was lower during the high power test at NRL than during the low power test at ANL is not completely understood, but may be due either to the uncertainties of the calibrations of the power detection circuit or to a change in the coupling due to a shift in the position of the tapered dielectric during transport. This will be taken into account next time by doing an in situ network analyzer measurement.

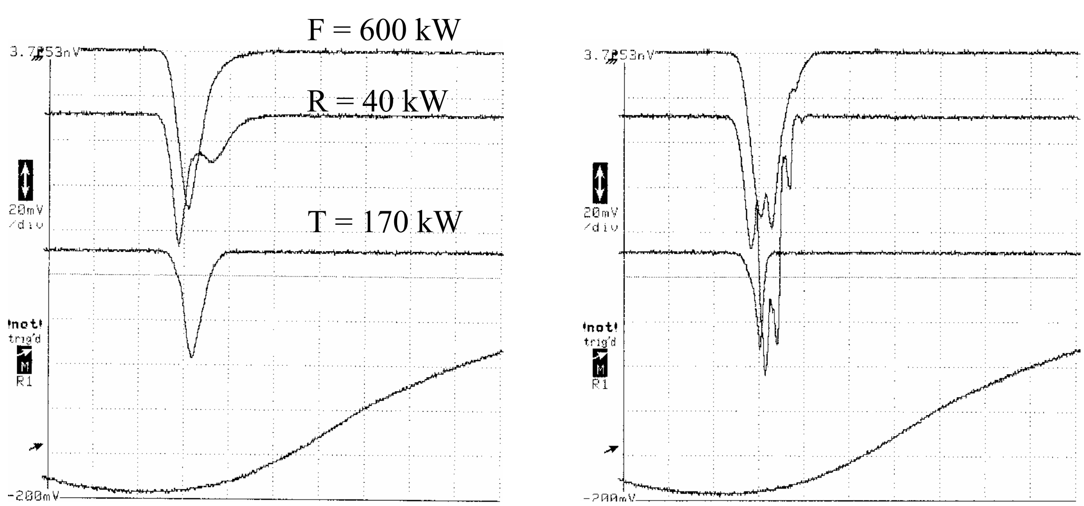


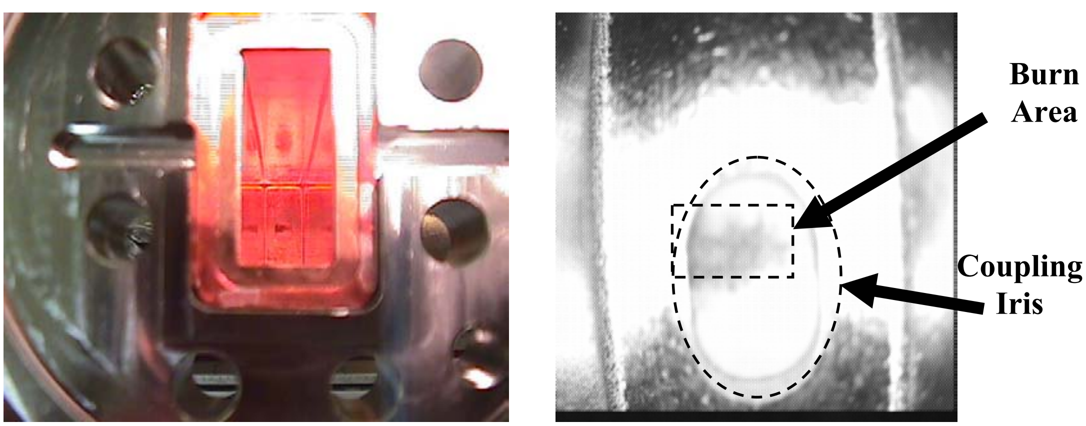
FIGURE 4. Input, Reflected, and Transmitted RF power waveforms corresponding to a) acceleration gradient of 3-5 MV/m and b) arcing in the input waveguide.

At the next increment in power (Fig. 4b), the RF waveforms from the input waveguide's bi-directional coupler (Fig. 2) became erratic, indicating that persistent arcing was occurring somewhere in the system. During the test, it was suspected that the arcing was occurring at the input coupling iris, since the pressure indicated by IP4 jumped with each arc while the other ion pump pressures did not. We ruled out dielectric breakdown of the TW-DLA structure itself since (1) the faraday cup ammeter continued to register zero current; (2) no flashes of light were seen inside the structure; and (3) the pressure readings nearest to the structure did not increase. After the arcing occurred at this elevated power level, the coupling iris appears to have become damaged since it continued to arc even when the power was reduced to previous levels where no arcing had been observed. After the high power test was completed, the structure was disassembled for examination. At that time it was confirmed that the input coupler had indeed failed since there was a visible burn mark (similar to the one shown in Fig. 5) along the center of the input coupling window.

We believe that the input coupler for the TW-DLA structure failed because the power density exceeded the maximum operating conditions (Power density ≈ 1 MW/cm^2) for ceramic windows. Simulations done after the high power test on the coupling window confirmed that the damage had occurred near the point of maximum electric field. Using 600 kW for the input power and taking the cross section of the coupling iris to be 27 mm^2 (from Table 1), we calculate a power density of about 2.2 MW/cm^2 – in excess of normal operating conditions.

Standing-Wave Accelerating Structure Test

During the high power test of the standing-wave structure, the magnicon output pulse width was again varied from 200 nsec at the beginning to 600 nsec at the end. This time, however, we were not able to significantly condition the SW-DLA structure beyond a few 10's of kW, since the coupling into the structure was poor from the onset. This meant that the power levels inside the structure were too low to allow for conditioning.



(A) (B)

FIGURE 5. Visible damage to the standing-wave coupling iris: a) color picture taken from above the input flange and b) close-up picture of the iris taken with a bore scope.

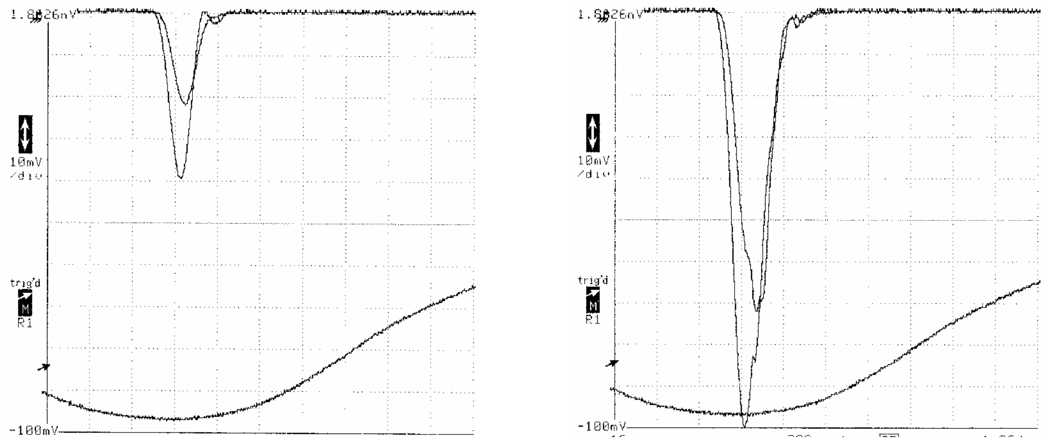


FIGURE 6. Input and Reflected RF power waveforms a) 50% of the power is reflected at very at forward power ~ 10 kW and b) 70% of the power is reflected at forward power ~ 40 kW.

At very low input power (Fig 6a. ~10 kW) there were no signs of arcing and the reflection coefficient (S_{11}) was about -3 dB, indicating that 50% of the power was being reflected from the cavity. At slightly higher power levels (Fig. 6b, ~40 kW), arcing appeared in the RF waveforms, pressure increased at IP4, and the reflected power increased further to about 60%. Finally, at about 100 kW, there was arcing, elevated pressure at IP4, and all the power was reflected. We believe these events were due to a large standing wave in the input waveguide due to a power sensitive mismatch of the coupling slot. Once again, the structure was disassembled after the high power test, and this time it was seen that the coupling window (Fig. 5) was covered with a copper residue. We believe that this copper residue acted to reflect the input power and that the effect worsened at higher power levels since the copper points acted as field emitters. The presence of the copper residue on the dielectric was likely the result of copper being scraped off the wall when the ceramic was loaded into the waveguide. This appears to be an unavoidable problem for this structure design, due the tight fit between the outer radius of the dielectric and the inner radius of the copper waveguide. The damage of the input coupling iris seen in both structures appears similar to what was observed in Ref. 12.

FUTURE DIRECTIONS

Based on what we have learned from the failure of the input coupling iris on the prototypes, both the TW-DLA and SW-DLA have been redesigned to eliminate the problems observed. The details of the new DLA structure is covered in Ref. [13], so only a brief summary will be given here.

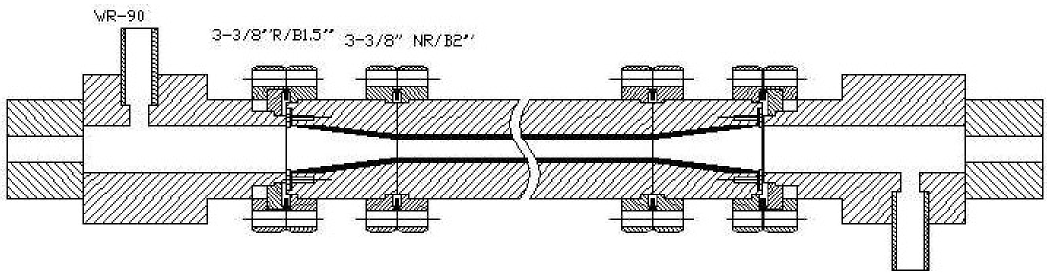


FIGURE 7. The Modular DLA Structure.

A new modular DLA structure (Fig. 10) has been designed. Moving from left to right in Fig. 10, we see that the new device consists of an all-metal TE-TM input coupler, an input tapered dielectric matching section, a constant radius dielectric accelerating section, an output tapered dielectric matching section, and an all-metal TM-TE output coupler. The lack of dielectric in the coupler solves the two problems encountered with the previous structure (1) since the slot's cross section is now bigger by a factor of 6.3 and there is no triple-point of dielectric-metal-vacuum, it should operate at higher power, thus solving the problem seen with the TW DLA structure; and (2) copper residue on the ceramic will have no effect on coupling. The new couplers are currently under construction and the rest of the modular accelerating structure has been designed and construction will begin soon. The entire series of high power tests will be repeated as soon as the structure is completed.

SUMMARY

In the second phase of a program to develop a compact accelerator based on a dielectric-loaded accelerating structure, we have conducted high power tests on a traveling-wave and a standing-wave prototype. Indications are that the traveling-wave structure achieved an accelerating gradient of 3-5 MV/m before the input coupling window failed, while the standing wave structure was poorly matched at high power due to contamination of copper residue on its coupling window. To solve both of these problems, a new method for coupling RF into the structures has been developed. The new couplers and the rest of the modular structure are currently under construction and will be tested at NRL shortly.

ACKNOWLEDGMENTS

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